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High resolution seismic imaging of faults beneath Limón Bay, northern Panama Canal, Republic of Panama

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Abstract

High-resolution seismic reflection profiles from Limón Bay, Republic of Panama, were acquired as part of a seismic hazard investigation of the northern Panama Canal region. The seismic profiles image gently west and northwest dipping strata of upper Miocene Gatún Formation, unconformably overlain by a thin (< 20 m) sequence of Holocene muds. Numerous faults, which have northeast trends where they can be correlated between seismic profiles, break the upper Miocene strata. Some of the faults have normal displacement, but on many faults, the amount and type of displacement cannot be determined. The age of displacement is constrained to be Late Miocene or younger, and regional geologic considerations suggest Pliocene movement. The faults may be part of a more extensive set of north- to northeast-trending faults and fractures in the canal region of central Panama. Low topography and the faults in the canal area may be the result of the modern regional stress field, bending of the Isthmus of Panama, shearing in eastern Panama, or minor deformation of the Panama Block above the Caribbean subduction zone. For seismic hazard analysis of the northern canal area, these faults led us to include a source zone of shallow faults proximal to northern canal facilities.

Keywords: Faults; Neotectonics; Panama; Seismic reflection

1. Introduction

The Isthmus of Panama occupies a complex tectonic setting between the South America, Nazca, Cocos, and Caribbean plates (Fig. 1; Adamek et al., 1988; Kellogg and Vega, 1995). This complexity has made plate boundaries and recent tectonics of the Panama region difficult to discern, but there appears to be a rigid Panama Block caught between the four other plates (Adamek et al., 1988; Silver et al., 1990; Mann and Kolarsky, 1995; Kellogg and Vega, 1995).

The Panama Block's location between two continents and two oceans has made it important for scientific and economic reasons. The Isthmus of Pan-

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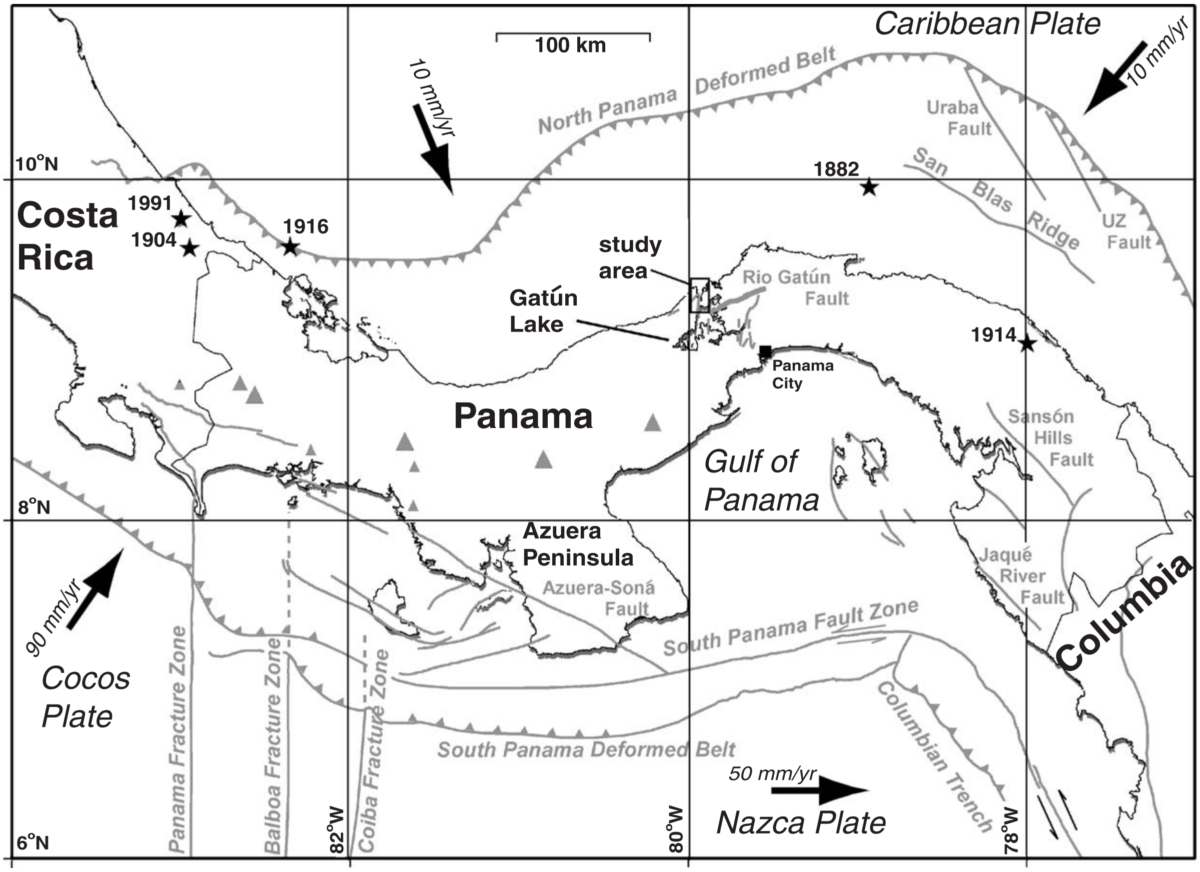

Fig. 1. Map showing the tectonic setting of Panama with relative plate motions from Trencamp et al. (2002). Features are described in the text. Stars show locations of earthquakes mentioned in text, gray triangles on land are volcanoes, gray lines are faults with barbs on hanging wall.

ama has been critical to determining ocean circulation, to controlling the distribution of fauna, and to the modern transportation network. Uplift of the isthmus in the Late Miocene and Pliocene allowed the migration of animals between North and South America, and cut off the flow of water between the Atlantic and Pacific oceans (Collins et al., 1996; Coates et al., 1992). The isthmus has been a major transportation conduit since Spanish conquistador and explorer Vasco Nuñez de Balboa first crossed it in 1513 and the 16th and 17th century Spanish hauled gold from Peru across the isthmus. More recently, the Panama railway was an immediate success when it opened in 1855, and the Panama Canal, completed in 1914, remains one of the world's major shipping routes.

The seismic hazard in central Panama has been a topic of debate since planning was begun for a trans-isthmian canal, and the tectonic complexity and surprisingly low level of seismic activity continue to produce large uncertainties in seismic hazard evaluation in central Panama (Camacho et al., 1997; Schweig et al., 1999). The relative seismic quiescence of Panama, and a fortuitous volcanic eruption in Nicaragua, was a decisive factor for the United States selecting Panama as the site of the trans-isthmian canal. However, strong shaking has been documented frequently in Panama since the European settlement (Kirkpatrick, 1921; Camacho and Viquez, 1993), the most severe being on September 7, 1882, the year the French began their unsuccessful attempt to build the Panama Canal. That event (M ~ 8) struck the north coast of Panama, shut down the railroad for a week for repairs, extensively damaged the town hall, and collapsed one tower of the cathedral in Panama City

(Mendoza and Nishenko, 1989). The associated tsunami killed about 70 people in the San Blas Islands north of the isthmus.

Before the Panama Canal was turned over to the Republic of Panama on December 31, 1999, the authors were requested to help in an assessment of the seismic risk facing Gatún Dam at the north end of the canal. Gatún Dam impounds Gatún Lake, whose waters allow ships to cross the isthmus and allow the canal locks to operate. For this assessment, we carried out geologic mapping, installed a temporary seismic array, and acquired high-resolution seismic reflection profiles in the northern canal area (Schweig et al., 1999).

This paper describes the high-resolution seismic imaging of faults in upper Miocene strata beneath Limón Bay, at the north end of the Panama Canal. The profiles, carried out in a reconnaissance style, were designed to search for faults and to determine whether any faults displace Holocene strata and therefore should be considered active. The study confirmed one suspected fault and revealed several other faults beneath the northern canal. After describing these faults, we speculate on several possible origins for the faults and we describe the impact their discovery had on our earthquake hazard evaluation of the northern canal facilities.

2. Geologic setting

The Isthmus of Panama is part of a Cretaceous to Holocene age volcanic arc formed in response to the subduction of Pacific oceanic lithosphere beneath the Caribbean plate in Central America (Fig. 1). The southern portion of the volcanic arc lies on the Panama Block at the junction between the Cocos, Nazca, South American and Caribbean plates (Adamek et al., 1988; Silver et al., 1990; Kellogg and Vega, 1995). The Panama Block is composed of Panama and southern Costa Rica, and seismic and geodetic studies indicate the western portion of the Panama Block is a rigid entity that is moving independently of the surrounding plates (Adamek et al., 1988; Freymueller et al., 1993; Kellogg and Vega, 1995; Trencamp et al., 2002).

Subduction zones bound the Panama Block on the north and southwest sides, and complex fault zones bound the south and southeast margins (Fig. 1; Kellogg and Vega, 1995; Cowan et al., 1998). Along the west side of the microplate, the Cocos plate is being subducted along the southern portion of the Middle America Trench (e.g., DeMets, 2001), which terminates at the Panama Fracture Zone (Adamek et al., 1988). The south side of the Panama Block is formed by a left lateral transform boundary, comprising the South Panama deformed belt and the South Panama Fault Zone (Okaya and Ben-Avraham, 1987; Silver et al., 1990; Westbrook et al., 1995), which accommodates eastward motion of the Nazca plate (Adamek et al., 1988; Kellogg and Vega, 1995).

Along the north edge of the Panama Block, the Caribbean plate is being subducted along the North Panama deformed belt (NPDB). An extensive accretionary prism along the NPDB has developed in response to the ~200 km of convergence since subduction started in the Miocene (Kellogg and Vega, 1995; Silver et al., 1990; Reed and Silver, 1995; Silver et al., 1995). The NPDB has been the source of large earthquakes in 1882, 1904, 1914, 1916, and 1991 (Fig. 1; Mendoza and Nishenko, 1989; Camacho and Viquez, 1993; Plafker and Ward, 1992; Goes et al., 1993; Montero et al., 1998).

The southeast edge of the Panama Block, along the Panama–Colombia border, is the South America–Panama arc collision zone. This region contains a series of thrust and right-lateral strike-slip faults that are part of a deformation zone extending into South America (Kellogg and Vega, 1995; Trencamp et al., 2002). This region has accommodated 150–200 km of convergence since the Late Miocene (Dengo and Covey, 1993; Kellogg and Vega, 1995) and the collision is thought to have produced the distinctive 'S' shape of the isthmus (Silver et al., 1990; Mann and Corrigan, 1990). In southeast Panama, the collision is expressed as a series of northwest-trending thrust and left-lateral strike-slip faults, including the Sansón Hills and Jacqué River Faults (Fig. 1; Mann and Corrigan, 1990; Mann and Kolarsky, 1995; Cowan et al., 1998).

In contrast to the margins described above, the interior of the Panama Block is characterized by low rates of internal deformation (Kellogg and Vega, 1995; Trencamp et al., 2002), low rates of seismicity even at very small magnitudes (Adamek et al., 1988), and low topography. These features must be reconciled with evidence that oceanic lithosphere has been subducted recently beneath the isthmus, as implied by the occurrence of recently active volcanoes at several localities along the Cordillera Central (de Boer et al., 1988; Drummond et al., 1995). Johnston and Thorkelson (1997) and Abratis and Wörner (2001) speculate that an oceanic spreading ridge has been subducted beneath the Panama Block, creating a "slab window" that lacks a subducted plate and its associated seismicity.

3. Stratigraphy of the northern canal region

The stratigraphic units in the northern canal region are described in Jones (1950), Woodring (1957), Stewart et al. (1980), Coates et al. (1992), and Collins et al. (1996). Strata consist of a Miocene to Holocene sedimentary sequence deposited on eroded pre-Tertiary volcanic rocks. East of Limón Bay, the Miocene Gatún Formation was deposited directly on the erosional surface at the top of the pre-Tertiary volcanic rocks. In the islands in Gatún Lake, south of Limón Bay, Oligocene strata lie between the pre-Tertiary bedrock and the Gatún Formation, but the contact between these units is not exposed near the bay.

The lowermost sedimentary unit in the area around Limón Bay is the Middle to Late Miocene Gatún Formation (11.8–8.6 Ma; Coates et al., 1992; Collins et al., 1996). Gatún Formation strata are exposed to the east, south, and west of Limón Bay, and in small areas of bedrock south of the bay (Stewart et al., 1980; Coates et al., 1992). The Gatún Formation has a total thickness of about 500 m, and the strata, which consist of shallow marine sandstone, siltstone, tuff, and conglomerate, dip gently northwest (Woodring, 1957; Coates et al., 1992; Stewart et al., 1980). The top of the Gatún Formation lies at about 100-m elevation 5 km southwest of Limón Bay, and gradually decreases in elevation to below sea level at the Caribbean coast (Stewart et al., 1980; Coates et al., 1992).

Conformably overlying the Gatún Formation is the Late Miocene (8.3–5.8 Ma) Chagres Sandstone, with the Toro Point Member at its base (Jones, 1950; Coates et al., 1992; Collins et al., 1996). The Chagres Sandstone is a massive, fine-grained sandstone and siltstone, with little or no evidence of bedding. The basal unit of the Chagres Sandstone, the Toro Point Member, is described as limestone by Jones (1950) and as a calcareous coquina by Coates et al. (1992).

The Pleistocene and Holocene Atlantic Muck unconformably overlies the Gatún Formation and Chagres Sandstone in localized areas (Jones, 1950). The Atlantic Muck consists of swamp deposits of clay, silt, and fine sand with abundant decayed wood and other organic matter. The Muck was deposited to depths of over 60 m in valleys eroded into the underlying units, and Atlantic Muck fills the upper parts of 50–80-m-deep channels beneath Gatún Dam 5 km south of Limón Bay (Fig. 2). The Atlantic Muck intergrades with the Chagres Alluvium, with which it

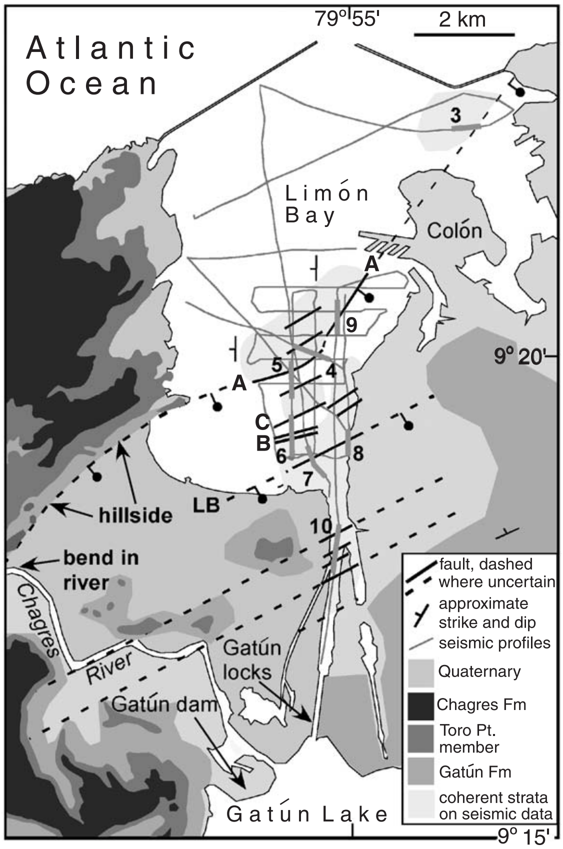

Fig. 2. Map of Limón Bay, at the north end of the Panama Canal, showing the locations of faults (black lines) interpreted from the seismic reflection profiles. The letters 'A', 'B', 'C', and 'LB' denote faults discussed in the text. The faults are interpreted to have normal displacement (ball on downthrown side) and a northeast trend (see text). Wide gray lines on the tracklines show locations of Figs. 3–10, with figure numbers labeled.

Table 1
Radiocarbon ages in "Atlantic muck" from cores at Gatún Dam, Republic of Panama

Site sample no./ Lab sample no.	Measured C14 age	C13/C12 ration 0/00	Conventional C14 age	Cal year (2σ)[a]	Comments
GDI-7-9/Beta-104413	5290 ± 60	-29.1	5220 ± 60	BC 4220–3945	9.6 to 9.7-m elevation, Wood
GDI-7-8/Beta-104412	5340 ± 50	-27.4	5300 ± 50	BC 4250–3985	9.7 to 9.8-m elevation, Wood
GDI-7-7/Beta-104411	5790 ± 60	-25.5	5780 ± 60	BC 4785–4485	9.8 to 9.9-m elevation, Wood
GDI-7-6/Beta-104410	5740 ± 50	-26.5	5710 ± 50	BC 4700–4455	9.9 to 10-m elevation, Wood
GDI-7-5/Beta-104409	7210 ± 80	-29.6	7140 ± 80	BC 6135–5805	-35.5 to -36.0-m elevation, Dispersed organics
GDI-7-5/Beta-104408	7080 ± 70	-28.5	7020 ± 70	BC 5980–5705	-38.0-m elevation, Dispersed organics
GDI-7-3/Beta-104407	7190 ± 60	-28.5	7140 ± 60	BC 6045–5855	-38.2-m elevation, Dispersed organics
GDI-7-2/Beta-104406	7310 ± 80	-29.6	7240 ± 80	BC 6195–5950	-38.3-m elevation, Dispersed organics
GDI-7-1/Beta-104405	8000 ± 90	-25.0	7970 ± 90	BC 7055–6570	-41.1-m elevation, Wood

[a] Calendar years calculated using the Pretoria procedure (Talma and Vogel, 1993; Vogel et al., 1993).

is grouped on maps, and the two units underlie nearly all flat surfaces below about 8-m elevation in the northern canal region (Jones, 1950). Radiocarbon ages for the Atlantic Muck obtained in geotechnical borings beneath Gatún Dam are conformable and range from about 7800 to 9000 years BP at elevations near -40 m to 5900–6800 years BP just above sea level (Table 1).

4. Seismic reflection data

We collected single-channel seismic reflection data throughout Limón Bay and the entrance to Gatún locks, on the Caribbean side of the Canal (Fig. 2). An initial reconnaissance of the Bay was carried out in 1996, and a grid of profiles in the south part of the bay was acquired in 1997. The data were collected from a

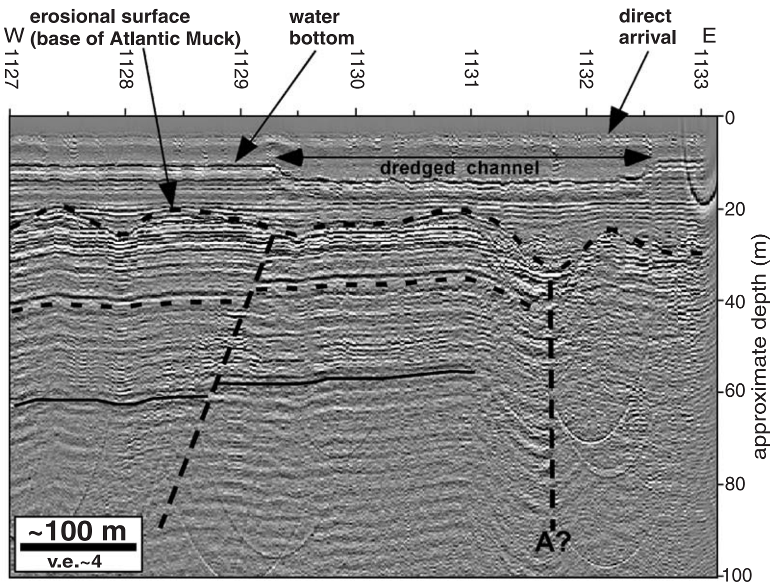

Fig. 3. Portion of profile LB-6 from the northeast part of Limón Bay. Prominent layered strata interpreted to be Gatún Formation are unconformably overlain by subhorizontal strata interpreted to be Atlantic Muck. The deeper strata are cut by a normal fault and perhaps by the northeast extension of fault A at the southeast edge of a large block of strata (see text). Solid and dashed lines mark two prominent reflectors to aid in correlating strata across the fault. U-shaped artifacts are noise spikes smeared in the migration process. See Fig. 2 for location. Data are migrated and converted to depth using a velocity of 1500 m/s.

small (~10 m) launch using a 300-J Uniboom seismic source triggered every 0.5 s. The Uniboom source was recorded on a 9-m-long, single-channel hydrophone array using a PC-based acquisition system (the USGS Mudseis system). A 0.4-s data length was recorded using a 0.00025-s (0.25 ms) sample rate. The position of the boat, which was moving at about 3.0 knots (~5.5 km/h), was recorded every 30 s using a Global Positioning System (GPS) receiver used in a differential mode except when the base station signals were not being received.

Data processing consisted of a bandpass filter (60–1100 Hz), time-variant gain ($t^{1.4}$), and deconvolution (4-ms gap, 0.12-s filter) to decrease reverberations and cyclic noise. Migration was tried, but the single-channel data do not provide velocity information for accurate migrations. Furthermore, a loose electrical connection in one of the streamer elements caused prominent noise spikes in the data. We removed most of these noise spikes, but those that remained spread into broad, high-amplitude artifacts when migrated (e.g., Fig. 3). The migration process therefore resulted in mixed success, and the profiles presented here consist of both unmigrated and migrated sections. When migrated, we used a constant velocity (1500 m/s) and a Stolt (f–k) migration algorithm.

The data are displayed as grayscale images with acquisition time (distance) along the horizontal axis and depth in the vertical direction (assuming a 1500 m/s velocity). The time of day marks along the horizontal axis correspond to about 100-m distance/min, or about 1 km/10 min. True depths are likely greater than indicated on the plots because the velocity is likely greater than the 1500 m/s used for time-to-depth conversion. The data displayed here have a vertical exaggeration of about 4.

5. Results

The seismic reflection profiles from Limón Bay image a prominently stratified sequence, unconformably overlain by a thin cover of subhorizontally bedded sediments (Figs. 3 and 4). The stratified sequence below the unconformity consists of parallel reflectors that are nearly horizontal (Fig. 3) or dip as much as 7° to the west or northwest (Fig. 4). The sequence extends to approximately 100 m maximum depth of signal penetration, and consists of coherent blocks separated by areas having weak signal penetration or a chaotic signature (Figs. 4 and 5). These areas of weak or chaotic appearance are likely caused

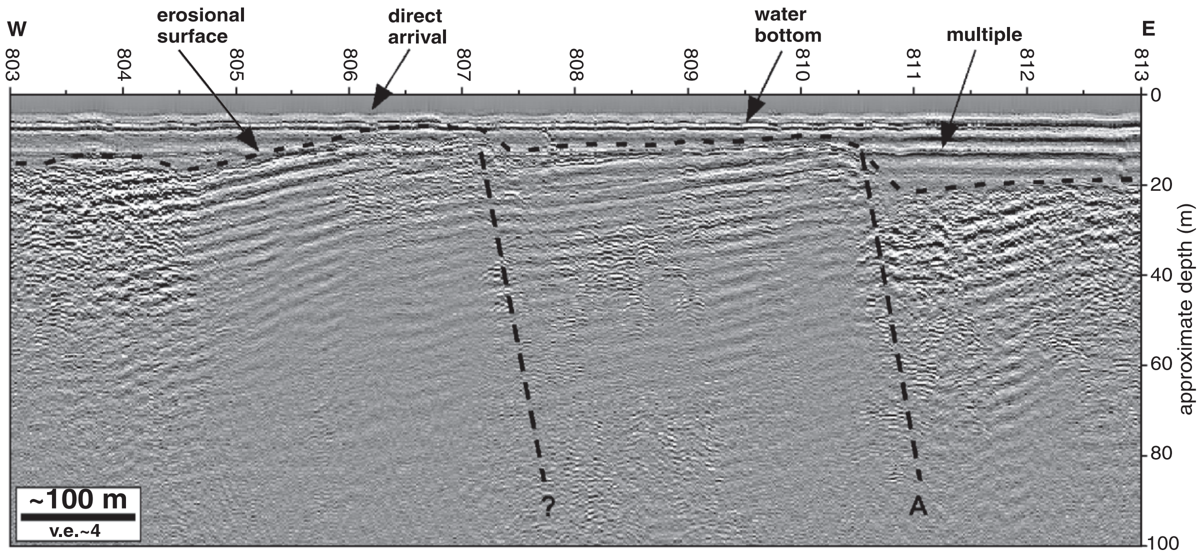

Fig. 4. Portion of seismic profile LB-3 showing northwest-dipping layered strata beneath Limón Bay cut by one and perhaps two faults. Fault A forms the southeast edge of a prominent block of strata and is visible on all the profiles in the area. See Fig. 2 for location. Data are migrated and converted to depth using a velocity of 1500 m/s.

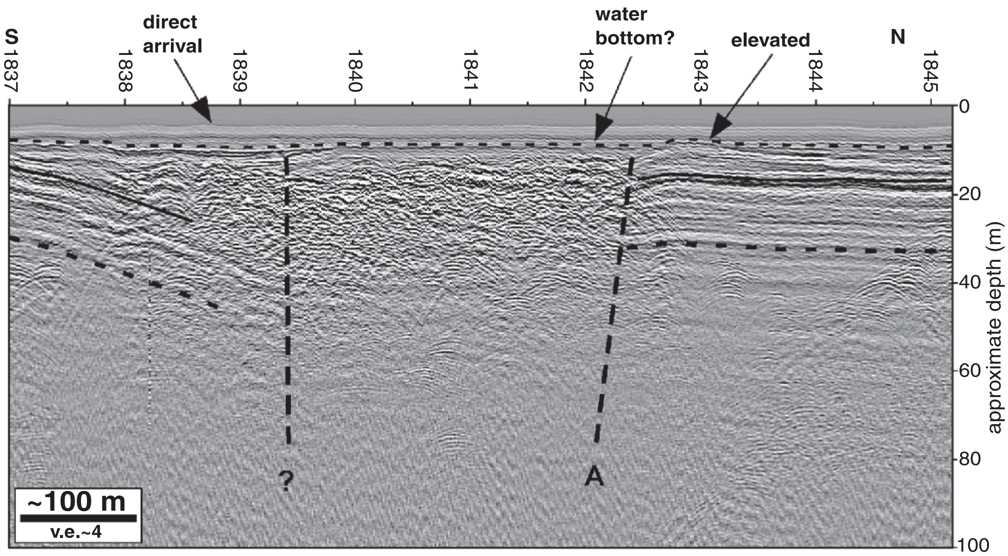

Fig. 5. Portion of seismic profile 18 showing fault A and the broad (~ 300 m) zone of chaotic reflectivity southeast of the fault. There could be two or more faults in the chaotic zone. Note that the coherent strata form an elevated part of the unconformity, suggesting recent uplift of these easily eroded strata. Solid and dashed lines mark two prominent reflectors to aid in correlating strata across the fault. The zone shows about 20 m of displacement, down to the south, but the strata return to about the same elevation about 600 m south of the fault. See Fig. 2 for location. Data are unmigrated but are converted to depth using a velocity of 1500 m/s. Vertical line below 1838.2 is a trace contaminated by electrical noise.

by disruption of the seismic signal by gas at the base of the unconformity or within fractures in the stratified sequence.

We interpret the layered strata beneath the unconformity as shallow marine deposits in the upper part of the Gatún Formation. The Gatún Formation presumably extends to depths of about 400 m, because it is approximately 500 m thick and its upper surface lies less than 100 m above sea level west and southeast of Limón Bay (Stewart et al., 1980; Coates et al., 1992). The northwest dip of the strata imaged on the seismic profiles is consistent with the northwest tilt of the Gatún Formation (Stewart et al., 1980). This regional tilt brings Tertiary and pre-Tertiary igneous rocks to the surface about 10 km southeast of Limón Bay (Stewart et al., 1980).

Above the unconformity at the top of the Gatún Formation, the sub-horizontal sedimentary strata thicken northward to as much as 20 m in the north part of Limón Bay (Fig. 3). The shallow sediments pinch out toward the southern part of the bay, where they are restricted to small depressions in the increasingly shallow erosional surface (Fig. 6). These shallow sediments consist of silts and muds that are easily dredged to make deeper shipping channels (e.g., Fig. 3), and we therefore interpret these strata as Pleistocene and Holocene deposits equivalent to the Atlantic Muck and Chagres Alluvium. These units underlie the surrounding lowlands and fill the channels beneath Gatún Dam (Fig. 2; Jones, 1950). If our interpretation is correct, the shallow strata above the unconformity are Holocene deposits whose age is the same or younger than the 7800–9000 years BP age of the Atlantic Muck at the base of the channel beneath Gatún Dam (Table 1).

The Gatún Formation strata beneath Limón Bay are broken by numerous faults (Figs. 3–10). Thirteen distinct faults or fault zones are visible on one 3.3-km length of profile (part of which is shown in Fig. 6) for an average spacing of only 250 m between faults in this area. These faults are evident both as individual faults (Figs. 3 and 4) and up to 300-m-wide zones of disrupted strata that could include two or more faults (Figs. 5 and 6). Our interpretation for the chaotic signature in these disrupted zones is that the faults serve as conduits for gas escaping from the organic-

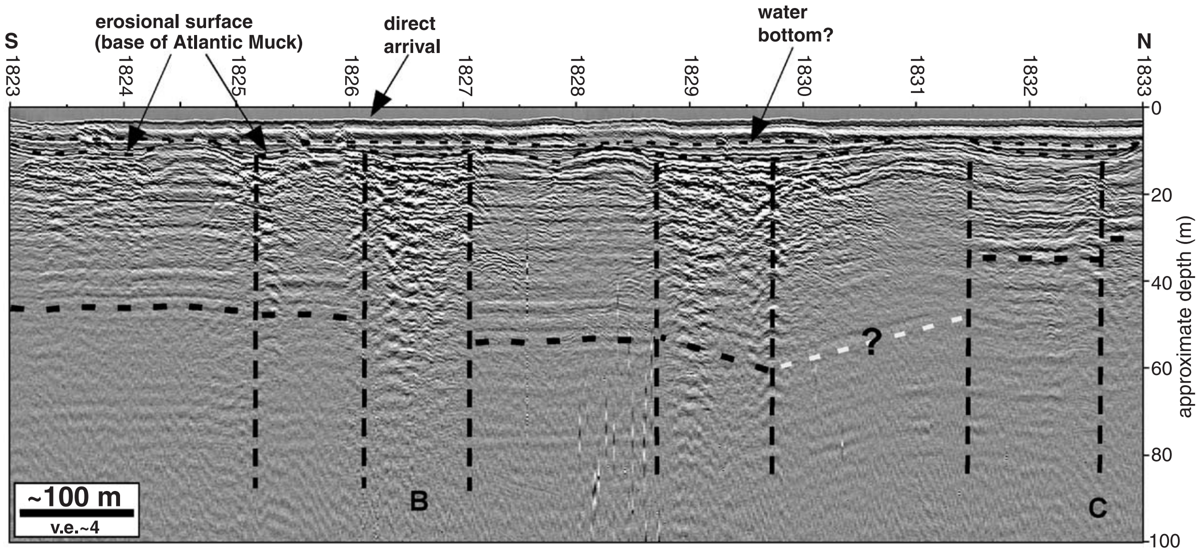

Fig. 6. Portion of seismic profile 18 showing possible near-vertical faults (vertical dashed lines) and the thin sequence of muds above the shallow unconformity. The heavy dashed line marks a prominent horizon. Correlation of the horizon across the faults at 1829.7 and 1831.5 is uncertain (white dashed line). Data are unmigrated but are converted to depth using a velocity of 1500 m/s. Vertical lines below 1828 are traces contaminated by electrical noise.

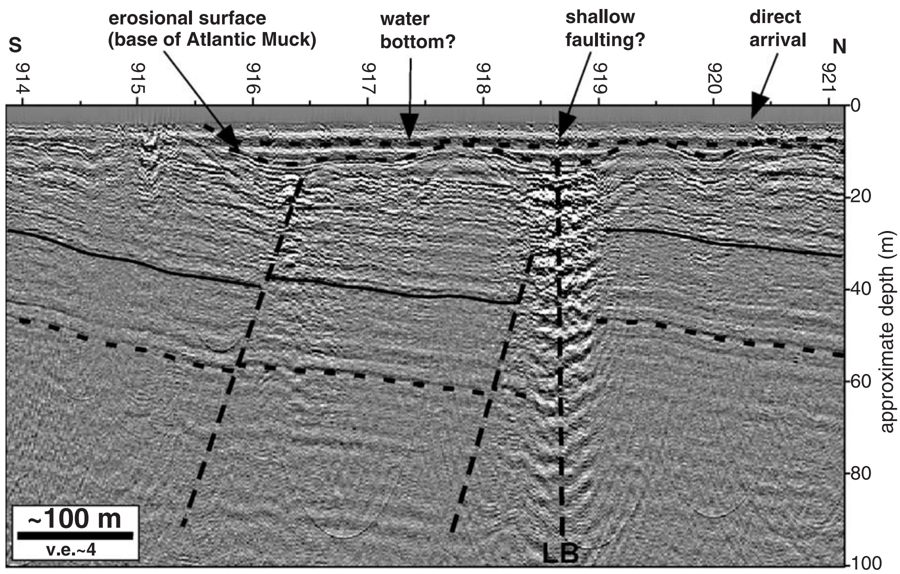

Fig. 7. Portion of seismic profile LB-5 showing fault LB and two nearby faults. Fault LB has about 16 m of vertical displacement, down to the southeast, hidden within the disrupted zone. The adjacent faults are identified from small displacements. Fault LB may be a normal fault like the adjacent faults, or the faults could represent two different styles and ages of faulting. Solid and dashed lines mark two prominent reflectors to aid in correlating strata across the fault. See Fig. 2 for location. Data are migrated and converted to depth using a velocity of 1500 m/s.

rich sediment, resulting in the disruption of the seismic signal in many of the fault zones. Although a disrupted zone coincides with most of the faults, we did not interpret a fault unless displacement was apparent across the zone. All of the profiles from the southern part of the bay and along the entrance channel to Gatún locks show faults, but there appear to be fewer faults in the northwest part of the bay. Profiles acquired within Gatún Lake showed little sub-bottom penetration, so it is not known whether this zone of dense faulting continues beneath and south of Gatún Dam.

Many of the faults we imaged appear to be steeply dipping (>60°), but others have shallower dips and a normal sense of separation (Figs. 3 and 7). The precise attitudes of many of the faults are unclear from the seismic profiles because the zones of high-amplitude, chaotic reflectors obscure the fault planes (Figs. 4–8). Nearby faults sometimes have opposite senses of apparent displacement (Fig. 6), but strata on the northwest sides of the faults are most often elevated relative to those on the southeast sides (Figs. 4, 5, 7 and 8). The faults may represent a single episode of faulting, or there could be two phases with differing fault styles (dipping normal faults, and near-vertical faults having reverse, normal, or strike-slip displacement). The amount of horizontal displacement on the faults is unknown, but the near-vertical attitude and sometimes opposing senses of vertical displacement are consistent with at least some strike-slip motion.

Correlation between seismic profiles indicates that several of these faults have a northeast trend, some approximately parallel to the Caribbean coast in the area (N60°E). Two of the most prominent faults, A and LB, serve as examples. Fault A, one of the most obvious features on the seismic profiles, lies at the abrupt southeast edge of a large block of coherent strata (Figs. 4, 5 and 9). This south edge is visible on all of the profiles in south–central Limón Bay (Fig. 2). If we follow the trend of A to the northeast (Fig. 2), it comes close to a series of faults in the northeast corner of Limón Bay (Fig. 3), although this could be a fortuitous alignment of unrelated faults. Displacement on fault A is down to the southeast. The amount of displacement cannot be determined on many of the profiles. One profile shows at least 20 m of displacement across fault A (Fig. 5), but the strata bend back to the same depth about 600 m from the fault on this profile.

Fault LB is visible on several profiles spanning a distance of about 1 km (e.g., Figs 7 and 8). The fault has 16–20 m of displacement, down to the south,

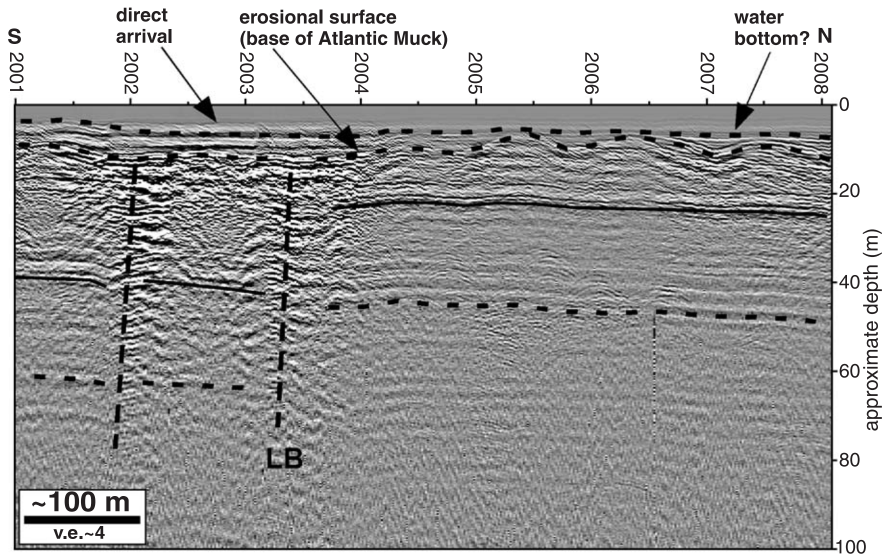

Fig. 8. Portion of seismic profile 21 showing fault LB and two nearby faults. Fault LB has about 16 m of vertical displacement, down to the southeast. Correlation with the fault shown in Fig. 6 gives a northeast trend for the fault (Fig. 2). Solid and dashed lines mark two prominent reflectors to aid in correlating strata across the fault. Data are unmigrated but are converted to depth using a velocity of 1500 m/s.

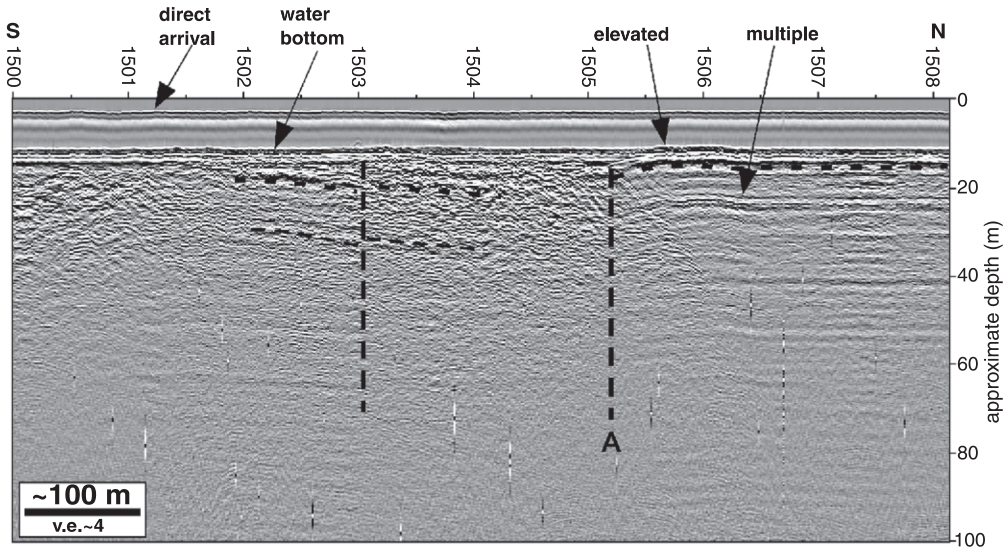

Fig. 9. Portion of seismic profile 12 showing fault A. See Fig. 2 for location. Solid and dashed lines mark two prominent reflectors to aid in correlating strata across the fault. Data are unmigrated but are converted to depth using a velocity of 1500 m/s. Vertical lines are traces contaminated by electrical noise.

across an approximately 70-m-wide zone. On one profile, there is a clearly imaged normal fault just to the south of LB that suggests normal motion on both faults (Fig. 7); however, these two faults could also be caused by two distinct phases of faulting having different fault attitudes and styles.

Geomorphic and geologic features are consistent with at least some of the faults extending beyond the edges of Limón Bay. In particular, fault A trends toward a peninsula, along a prominent hillside, and toward a distinct bend in the Chagres River (Fig. 2). All of these topographic features coincide with the south edge of bedrock on the west shore of Limón Bay. This evidence led Jones (1950) to infer a fault at this location, and all of the features are consistent with a fault at the south edge of an uplifted block of bedrock as we imaged at fault A (Figs. 4, 5 and 9). Faults imaged in the channel between Limón Bay and Gatún Locks (Fig. 10) also align with the edges of bedrock outcrops and distinct bends in the Chagres River if they have a northeast trend (Fig. 2). These river bends could be caused by river diversion due to uplift or by the river following fractured rock in fault zones.

Motion on the faults we imaged beneath Limón Bay post-dates the Late Miocene Gatún Formation, which is known from foraminifera to be late Middle to Late Miocene in age (11.8–8.6 million years ago; Collins et al., 1996; Coates et al., 1992). Where the strata beneath Limón Bay are cut by faults, the equal thickness and parallel bedding of strata on both sides of the fault indicate that deposition was completed before the fault moved. Had faulting progressed during deposition (growth faulting), strata on the down-dropped side would be thicker and the dip of the strata would increase with depth.

There may be Quaternary and Holocene displacement on some of the faults beneath Limón Bay. Fault A is bounded on the northwest by a prominent, uplifted block that appears to form an elevated area on the water bottom (Figs. 5 and 9), or form sharp uplifts in the erosional surface (Fig. 4). The Gatún Formation strata are only semi-consolidated and are easily eroded, so these elevated areas suggest recent motion. One of the shallowest layers, at a depth of about 10 m, appears to be broken above fault LB with about 1 m of apparent vertical displacement (Fig. 7). A nearby profile across the same fault could also be interpreted as showing a small displacement in the shallow strata (Fig. 8). Our data have insufficient resolution to confidently interpret a break on these profiles. However, this apparent break may indicate

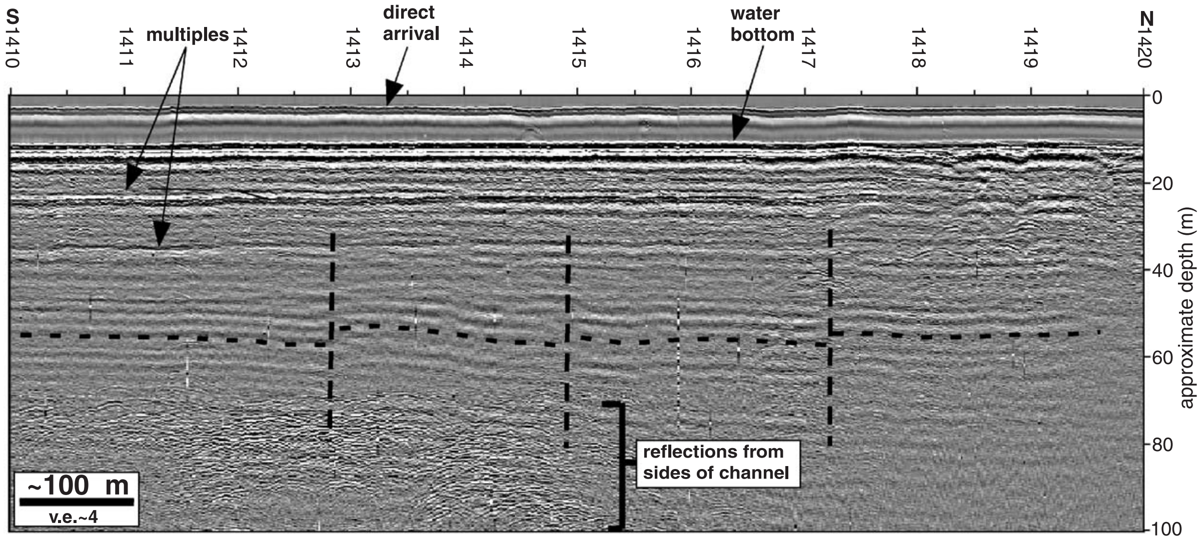

Fig. 10. Portion of seismic profile LB-12 acquired in the entry channel to Gatún locks, showing faults within 3 km of the locks. The trends of these faults are unknown, but if they have a northeast trend, they align with the edges of bedrock and with sharp bends in the Chagres River, consistent with faulting (Fig. 2). Dashed lines mark a prominent reflector to aid in correlating strata across the faults. Data are unmigrated but are converted to depth using a velocity of 1500 m/s. The high-frequency reflections at 60 to 100 m are from the sides of the channel.

that fault LB has had Holocene motion if the muds above the unconformity are Atlantic Muck or Chagres Alluvium, as we hypothesize above. The youngest age of displacement on the other faults is unconstrained by our data, in part because dredging has removed the shallow deposits beneath some of our profiles.

An estimate of the maximum displacement on the faults can be made from geologic information. The contact between the Gatún Formation and the overlying Chagres Formation lies at about 100-m elevation near Gatún Lake, and gradually decreases to just below sea level at the Caribbean coast at the mouth of the Chagres River (Stewart et al., 1980). That this contact remains within about 100 m of sea level, despite bedding that dips at up to 7°, indicates that the regional tilt and the displacement across the faults cause less than about 100 m of total elevation change over a distance of about 8 km. This is consistent with our observation that the individual faults beneath Limón Bay have relatively small displacements (< 30 m). Most likely, the faults have broken the Gatún Formation strata into a series of blocks with rotated strata but little net elevation change. Such fault-bounded blocks are not evident in the Gatún Formation or overlying units on the geologic map (Stewart et al., 1980), but this is likely due to a lack of exposure in this densely forested region.

6. Relationship to other faults

The faults beneath Limón Bay may be part of a more extensive set of predominantly north- and northeast-trending faults mapped from outcrop and airborne radar imagery in the topographically low canal region (Fig. 11; Stewart et al., 1980; Lowrie et al., 1982; Schweig et al., 1999). Some of these faults and fractures are nearly parallel to the faults we see beneath Limón Bay, whereas others have a more northerly trend. Late Miocene and younger normal displacement are mapped on some of these faults, but there is evidence for reverse and strike-slip movement as well.

The most prominent of these northeast-trending faults is the Rio Gatún fault 15 km southeast of Limón Bay (Fig. 11). The Río Gatún fault is a ~ 30 km long, south-dipping normal fault that forms the south edge of the Sierra Maestra highlands (Fig. 11; Stewart et al., 1980; Mann and Corrigan, 1990;

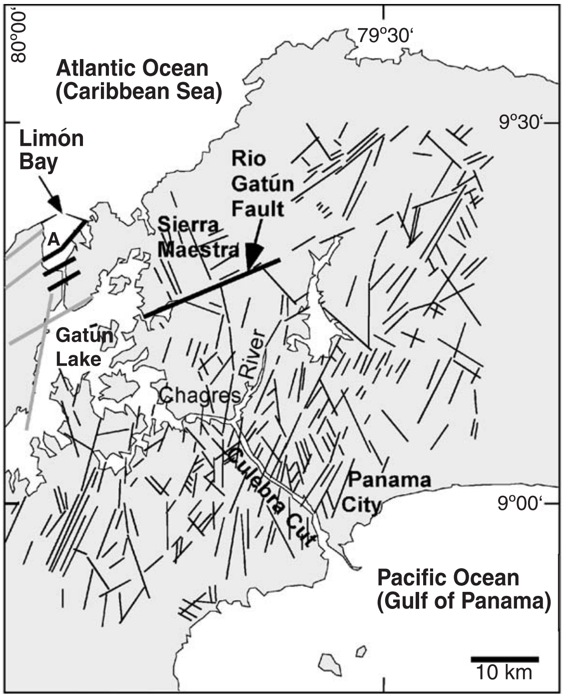

Fig. 11. Map of the canal area of Panama showing some of the north- and northeast-trending faults discussed in the text (bold black lines) inferred by Jones (1950) (bold gray lines), mapped along Culebra Cut by Stewart et al. (1980), and mapped from airborne radar by Lowrie et al. (1982).

Schweig et al., 1999). Slip indicators examined for this study indicate pure dip-slip motion, and the fault does not appear to displace structures laterally at its east end (Schweig et al., 1999).

There has been substantial Late Miocene and younger displacement on the Rio Gatún Fault, although there is no direct evidence of Holocene activity (Schweig et al., 1999). The large topographic front on the north side of the Rio Gatún Fault implies at least 900 m of uplift along the fault. The timing of uplift is uncertain, but the northwest tilt of the Late Miocene Gatún Formation along the west side of the Sierra Maestra indicates that a substantial part of the uplift and tilting occurred after the Late Miocene. Unfaulted, deeply weathered alluvial deposits crossing the Rio Gatún Fault suggest little or no Holocene displacement (Schweig et al., 1999). This lack of Holocene activity is also consistent with the low level of crustal seismicity in central Panama today ((Adamek et al., 1988; Camacho et al., 1997).

North- and northeast-trending normal and strike-slip faults are also exposed in Culebra Cut between Gatún Lake and the Pacific coast (Figs. 11 and 12; Stewart et al., 1980). These faults, exposed during various canal-widening projects but quickly covered with dense vegetation, displace Early Miocene units, filling the valley within which the canal was constructed. Individual faults are mapped with normal, right-lateral, or left-lateral displacement. Most of the mapped faults have about a N30°E trend (Stewart et al., 1980), about 30° different than most of the faults we imaged beneath Limón Bay but nearly parallel to the inferred northeast extension of fault A (Fig. 11). A Middle Miocene or younger age of movement on these faults is indicated by the lack of growth faulting in lower Miocene strata. The faults are mapped primarily in the canal area between Gatún Lake and Panama City (Stewart et al., 1980), but this limited extent could be due in part to limited exposures outside of the construction areas.

Lowrie et al. (1982) infer an extensive set of faults and fractures from lineations on airborne radar images (Fig. 11). They interpret the age of faulting on many of these structures as Middle Miocene or older because there are fewer lineaments visible on the upper Miocene and Pliocene rocks. However, the faults may be older structures having smaller amounts of post-Miocene displacement. The paucity of mapped faults in the Miocene and younger deposits could be due in part to the greater difficulty in detecting faults with relatively small displacements on flat areas covered with rainforest (with few road cuts). Our seismic reflection profiling is much more effective at detecting faults in the coastal lowland area.

The canal area of central Panama between about 79°W and 80°20′W, where this broad zone of faults and fractures occurs, lies in a region of relatively low topography with maximum elevations below 1200 m and four major valleys having elevations as low as 220 m (Lowrie et al., 1982). The most dramatic expression of this topographically low region is the large swamp and Chagres River valley that now lie beneath Gatún Lake (Fig. 11). The Chagres River penetrated to within 25 km of the Pacific Ocean in central Panama (Fig. 11), and Culebra Cut was dug along a saddle having a maximum elevation of less than 200 m. The faults we have imaged thus appear to be part of an extensively fractured region of low topography.

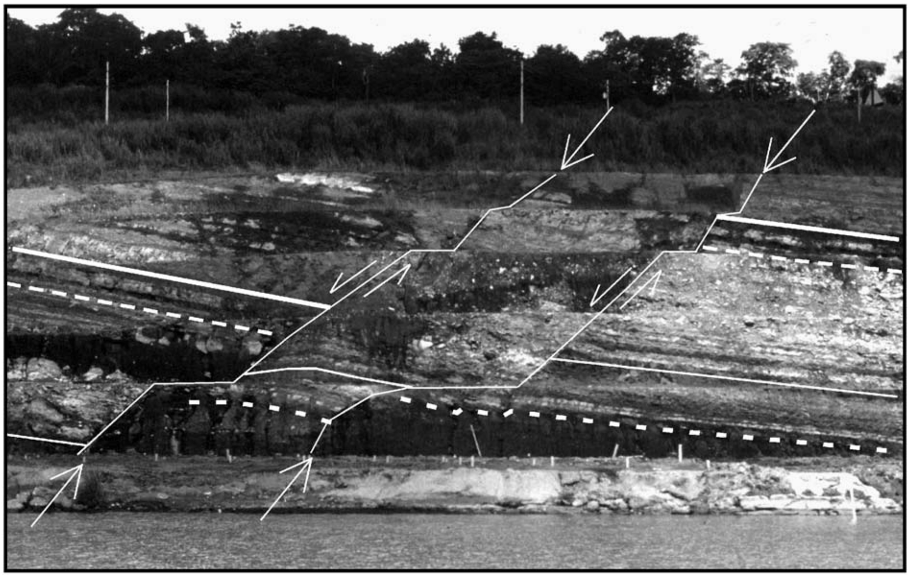

Fig. 12. Photograph of a normal fault along a nearly north–south section of Culebra Cut in the canal. Large arrows mark the tops and bottoms of two faults marked with thin white lines, with small half-arrows showing sense of displacement. Heavy and dashed lines dipping gently to the right mark the base of prominent strata that are displaced down to the left. The edge of the canal is stepped in a series of horizontal terraces that obliquely cut the faults and strata, making the faults appear to shift to the left. The cut face is about 30 m high (note the telephone poles and trees at the top of the hill).

Case (1974) interpreted the faults and low topography of the canal region to be part of a broad zone of deformation called the "Canal Discontinuity". Evidence for this discontinuity also includes the correlation of igneous rocks of Middle Eocene to Early Paleocene age (~ 48–62 Ma; Stallings et al., 1995; Maury et al., 1995) between the Canal region and the Azuero Peninsula (Fig. 1). The distribution of these rocks is interpreted as evidence for bending of the volcanic arc or for left-lateral offset along northwest-trending fractures in western Panama (Case, 1974). The hypothesized 'Canal Discontinuity' has also been interpreted as the eastern boundary of the Cocos plate in the Miocene (Lowrie et al., 1982). However, no direct geological or geophysical evidence for a major fracture zone has been documented. Marine geophysical and geological studies in the Gulf of Panama farther south have shown that the discontinuity, if it exists, must be older (and the related structures deeper) than the post-Middle Eocene to Pliocene unconformity beneath the Gulf of Panama (Mann and Kolarsky, 1995) and the post-Oligocene sedimentary succession in the Gatún Lake area (Woodring, 1957, 1982; this study). Any 'Canal Discontinuity' thus predates the displacement we document on the faults beneath Limón Bay, but we cannot eliminate the possibility that we are seeing post-Miocene reactivation of older structures associated with a 'Canal Discontinuity'.

7. Formation of post-Miocene faults in the northern canal area

As discussed above, the time of movement of the faults beneath Limón Bay is restricted to Late Miocene and younger, as the upper Gatún Formation was deposited before being faulted. This places a maximum age of about 8.6 Ma for the displacement we document on the faults, although they could overlie older structures that were reactivated after deposition of the Late Miocene deposits. The minimum age of displacement is unconstrained. Some of the faults could have Holocene motion, making them active from a seismic hazard perspective. Regional geologic considerations outlined below suggest that Pliocene activity was likely.

The Isthmus of Panama has risen and fallen in the past, allowing or restricting the flow of water between the Atlantic and Pacific oceans (Coates et al., 1992; Collins et al., 1996). The Gatún Formation (~ 11.8–8.6 Ma) was deposited in shallow water, and the benthic foraminifera within the formation show a strong Caribbean affinity. In contrast, the overlying Chagres Sandstone (~ 8.3–5.8 Ma) was deposited in deeper water (>200 m) with a Pacific affinity (Collins et al., 1996). These stratigraphic traits have been interpreted to indicate that the isthmus was just below sea level (~ 25-m depth) at 11–8 Ma, but deepened to about 200–500 m by about 6 Ma. By Late Pliocene times (3.5–2.5 Ma), the two oceans were entirely separate, implying the isthmus had once again risen above sea level.

One potential episode of normal faulting could have been from ~ 8 to ~ 6 Ma when the isthmus was subsiding to a depth of about 200 m. This subsidence could have occurred through extension along a broad zone of normal faults spanning the isthmus. This scenario implies growth faulting during deposition of the Chagres Sandstone, a hypothesis we can neither prove nor disprove using our data.

However, the significant relief evident on the unconformity imaged on the seismic data and along the onshore extension of some of the faults implies more recent movement (Pliocene or Quaternary), and the northwest tilt to the Gatún Formation and Chagres Sandstone requires post-Miocene regional tilting of the strata around Limón Bay. This tilt may have occurred while the isthmus was being uplifted between 6 and 2.5 Ma. Motion on the Rio Gatún Fault is responsible for at least part of this tilting, as deduced from the ~ 900 m of topographic relief on the Rio Gatún Fault at the south edge of the Sierra Maestra uplift. Because the faults we imaged are parallel to the Rio Gatún Fault, they may have responded to the same stresses and also moved during the tilting. We thus hypothesize Pliocene motion on the faults beneath Limón Bay. The amount of Quaternary movement, if any, is unknown.

Several potential mechanisms could cause the northeast-trending normal faults we imaged beneath Limón Bay. The faults may have formed in their current orientation, approximately parallel to the southwest direction of subduction of the Caribbean plate beneath eastern Panama (Adamek et al., 1988; Kellogg and Vega, 1995; Trencamp et al., 2002). Assuming the principle horizontal compressive stress is perpendicular to the southwest direction of Caribbean plate motion northeast of Panama (Fig. 1), the northeast-trending faults we imaged are suitably oriented for normal displacement. This normal faulting could also have a strike-slip component caused by shearing due to the opposing senses of motion of the subducting plates to the north and south of the Panama Block (Fig. 1). These stresses are still in place, suggesting that the faults could still be active.

However, a small number of focal mechanisms (Adamek et al., 1988) and north-trending thrust and reverse faults in the Gulf of Panama (Mann and Kolarsky, 1995) indicate a predominantly east–west compressive stress direction in Panama. This stress field has presumably been in place since the Late Miocene collision with South America. This east–west compression is believed to have produced the S-shape to the Isthmus of Panama by bending and northward motion (Silver et al., 1990) or by shearing and thrusting in southeast Panama (Mann and Corrigan, 1990; Mann and Kolarsky, 1995). In either the bending or shearing models, central Panama has moved (“escaped”) north relative to western Panama, resulting in an overall counterclockwise rotation of the central Panama region.

Given this rotation, the faults we imaged beneath Limón Bay may have formed with an east–west trend parallel to the Late Miocene compression (east–west), and have been rotated 20–30° counterclockwise into their current northeast trend during the bending. This is also a plausible interpretation if the faults we imaged are older, reactivated basement structures accommodating counterclockwise rotation of crustal blocks, but no paleomagnetic data are available to test this model. The more north-trending faults (Fig. 11) could have formed in a slightly different stress field before or in the early stages of the collision with South America, perhaps with later reactivation. The orientations of the faults would thus reflect the time of their formation in this changing stress field, although displacement could have continued, or minor reactivation occurred, at later times.

The pattern of extensional faulting in the canal region has also been hypothesized to be the result of normal faulting at the terminations of northwest-trending, left-lateral strike-slip faults documented in eastern Panama (e.g., Sansón Hills Fault, Jacqué River Fault; Fig. 1). In this model, the Canal region is an area of normal and left-lateral, strike-slip faulting between shear zones in eastern and western Panama (Mann and Corrigan, 1990; Mann and Kolarsky, 1995). This interpretation is plausible only if shearing is restricted to eastern Panama so as not to violate the geodetic data (Kellogg and Vega, 1995) and if the faults in the canal region have almost pure normal displacement consistent with field studies of the Rio Gatún Fault (Schweig et al., 1999).

Finally, the post-Miocene activity we document could represent an accommodation of mild strain within the Panama Block above the subducted Caribbean plate. Some strain is indicated by Pliocene to Pleistocene volcanic rocks, which may be associated with a slab window and upwelling of oceanic mantle beneath central and western Panama (Abratis and Wörner, 2001; Johnston and Thorkelson, 1997). This mechanism also implies continued activity on the faults in the canal region.

8. Implications for hazard assessment of the northern Panama Canal area

Previous hazard assessments of the northern Panama Canal were based primarily on seismicity (e.g., Camacho et al., 1997) or focused on two source zones in the northern canal area: the subduction zone 100 km offshore but extending beneath the Gatún Dam at a depth of about 35 km, and the Rio Gatún Fault. We also included these source zones in our assessment (Schweig et al., 1999), concluding that the subduction zone is capable of producing a M7.5–8.0 earthquake every 330–1000 years, and the Rio Gatún Fault is capable of a M6.8 earthquake every 10,000–20,000 years (although this recurrence interval is poorly known). Faults directly beneath or very near the canal structures, though suspected, had not been proven before our work.

The faults we imaged on the high-resolution seismic data were treated as a separate, proximal source zone in our seismic hazard analyses of the northern canal facilities. The evidence we describe above suggests a fault length of 8–13 km for at least one of the faults (fault A; Fig. 2). This length makes the fault capable of a M6.0 earthquake (Wells and Coppersmith, 1994), which we consider a reasonable upper bound for the faults close to the canal facilities. Most of the faults are shorter and would be capable of generating only smaller earthquakes.

To estimate the recurrence interval for earthquakes on the shallow faults, we included these faults with the Rio Gatún fault to encompass all crustal faults near the northern canal facilities. Assuming a Gutenberg–Richter *b*-value of 1 and a recurrence interval of 10,000–20,000 years for a M6.8 earthquake on the Rio Gatún fault, we estimated a 2000-year-recurrence interval for a M6.0 earthquake and 200 years for a M5.0 earthquake within 2 km of the facilities. These recurrence intervals are poorly constrained given our current state of knowledge.

The seismic reflection profiling, done in a reconnaissance mode, played a key role in our hazard analysis by documenting the faults near the northern canal facilities. Although the presence of faults in the area had been suspected because of topographic features and faults in the surrounding area (Jones, 1950), until our study, most of these structures were only inferred or had escaped detection completely because of the dense vegetation. Our original commission was to profile across a few specific targets, but the low cost of marine high-resolution profiling gave us the ability to explore a broader area than originally proposed. The result was the discovery of several new faults and the ability to determine the trends of the faults from multiple seismic profiles.

Key elements of the tectonic models for Panama need to be tested before we understand the causes of the faults we imaged in the tectonically complex canal area. These faults could represent a significant seismic hazard to the Panama Canal if they are still active. Especially crucial to understanding their origin is examination of the hypothesized shear faults in eastern Panama, better age constraints on the faults in the canal area, and knowledge of the deeper crustal and mantle structure. Geological mapping of the basement geology east of the canal, more detailed geologic, paleoseismic, and geophysical studies of potentially active faults, and deeper geophysical profiling beneath the approaches to the canal are thus prerequisites to a better understanding of the neotectonics of the isthmus and its economically strategic transport corridor.

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